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FINAL REPORT

DESIGN RULES FOR A 100X MAXIMUM EFFICIENCY GaAs CONCENTRATOR SOLAR CELL FOR SPACE APPLICATIONS

NASA Contract #NAG 3-321

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Submitted by

Allen M. Barnett
Department of Electrical Engineering
University of Delaware
Newark, Delaware 19711

SUMMARY

A miniaturized Cassegrainian concentrator system concept has been developed for low cost, multi-kilowatt space solar arrays.[1] Multi-kilowatt solar arrays can be assembled using these miniaturized Cassegrainian type optical concentrator elements. Significant system efficiency improvements and cost reductions are projected for gallium arsenide solar cells[2] particularly at concentration levels of 100 air-mass-zero suns.

Gallium arsenide solar cells offer the principal advantage for space concentrator applications of higher energy conversion efficiency. Other advantages include higher operating temperatures and the potential for improved radiation tolerance. The design rules for maximum efficiency GaAs solar cells for space applications have been developed under NASA contract #NAG3-321. The improved solar cell design was primarily based on the loss minimization technique. Loss minimization analysis has led to (1) the preference of N on P as the preferred structure rather than the common P on N structure, and (2) the design of an improved transparency top contact based on the separation of the grid and bus bars. The NASA contract also led (3) to the identification of gallium phosphide as an improved window layer, replacing the (GaAℓ)As. These three improvements will be developed under the follow-on contract.

INTRODUCTION

Gallium arsenide solar cells have been demonstrated with significantly higher energy conversion than silicon solar cells. Efficiency values as high as 18.8% under AMO illumination have been reported.[3,4]

GaAs solar cells have also demonstrated higher operating temperatures.[5] Other GaAs advantages, when compared to silicon, include higher specific power, increased radiation tolerance and an opportunity to anneal radiation induced defects.[6]

It has been shown that there are other advantages for the photovoltaic system, resulting from the reduction in solar panel area, which may warrant the use of GaAs provided the end-of-life advantage over silicon is at least 20 percent.[7] Since the GaAs solar cell initial efficiency can be 20% greater than silicon and there is a good potential for improved radiation tolerance, design and development of high efficiency GaAs solar cells for space applications which are based on a proven GaAs manufacturing technology can lead to a reduction in the time and the cost required to capitalize on this opportunity.

There are at least three GaAs solar cell configurations which have demonstrated high energy conversion efficiencies. All three of these configurations have been designed to reduce the current losses due to surface recombination. These losses occur at the top GaAs surface (closest to the sunlight). The primary role of this layer is to collect the minority carriers generated by the sunlight in the base region and to convert these minority carriers to majority carriers.

Two of these approaches are based on the growth of a (GaAl)As window layer on the top p-type GaAs layer. The recombination velocity at the (GaAl)As/GaAs interface is lower than that at the GaAs surface. This design is called the heteroface solar cell. Efficiencies up to 21.9% AM1 (equivalent to 18.8%) AMO) were reported in 1976[3] for a p on n structure with a GaAs p region thickness of 0.2 microns and a (GaAl)As thickness of 0.2 microns. In 1979, a p on n structure with a 5 micron thick p-GaAs region, an ultra-thin .05 micron, (GaAl)As window and a two-layer anti-reflection coating was reported with 18.8% AMO efficiency.[4] Minority carriers are generated in the p-GaAs region which is on top and are then transported to the n-GaAs collector-converter which is the bottom layer. Carrier transport is aided by the long electron minority diffusion lengths in the p-GaAs and probably aided by an electric field based on higher doping at the (GaAl)As/GaAs interface. The internal collection efficiency was calculated to be 93%.

The third configuration is based on a thin n-GaAs layer on p-GaAs.[8] This structure is called the shallow homojunction. The n-region is less than 0.02 microns thick and most of the light is absorbed in the p-GaAs. The n-region is thinned and an anti-reflection coating is applied by anodization. AMO energy conversion efficiencies of 17% (AM1 of 20%) have been reported.

All three of these configurations show promise as high efficiency GaAs solar cells for space applications. The heteroface structure is preferred for the 100X concentrator because the thin n-layer in the N or P structure leads to too high a series resistance.

The design was primarily based on an analysis in three specific technical areas. These areas are:

1. Analysis of the absorbed 100X AMO photon distribution in the solar cell.
2. Analysis of J_{sc} in the base (photon-absorber), emitter (minority carrier collector) and depletion regions.
3. Analysis of the top contact (resistance and reflection) losses.

Following is an overview of the design areas.

LOSS MINIMIZATION ANALYSIS

There are several design changes in the heteroface solar cell which can lead to improved efficiencies. These design changes were analyzed using the loss minimization technique reported elsewhere.[9] A review of the loss minimization analysis follows.

A design optimization for GaAs solar cells should lead to devices with theoretical efficiencies greater than 21% AMO (one sun) and 23% at 100 suns AMO. These theoretically predicted efficiencies are not observed because actual solar cells have losses which cause deviation from theoretical predictions.

Losses in initial performance can be grouped into optical losses, losses due to the photons of sunlight not being absorbed in a manner which leads to the generation of collectible minority carriers and electrical losses, those losses which reduce the optimum electrical parameters of the photovoltaic diodes. Interface losses in addition to the bulk losses for each of the five layers must also be considered. Losses in performance with time, or degradation losses, are changes in characteristics, either bulk or interface, which reduce performance over the long-term. Degradation losses will not be included at this time.

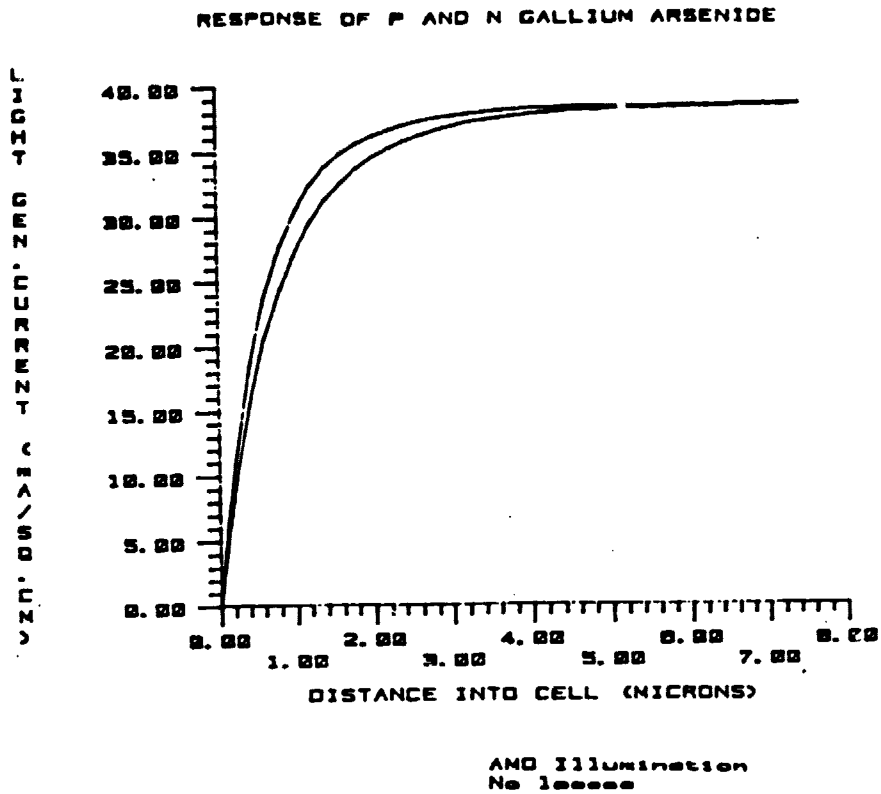
Following are the results of this loss analysis for optimized N on P and P on N 100X GaAs solar cells.

1. OPTIMIZED 100X GaAs CONCENTRATOR SOLAR CELL DESIGN

The optimized performance design can be derived by first maximizing current, then calculating voltage and maximizing the product of voltage and current and then minimizing device geometry, primarily resistance losses. The details behind these calculations are shown elsewhere.[10]

Current Generation

The maximum current can be calculated using the photon flux distribution and the absorption co-efficient leading to the distribution of generated minority carriers. Solution of the diffusion equation leads to the generated current. The maximum current that can be generated as a function of GaAs thickness is shown for P and N type material in Figure 1.



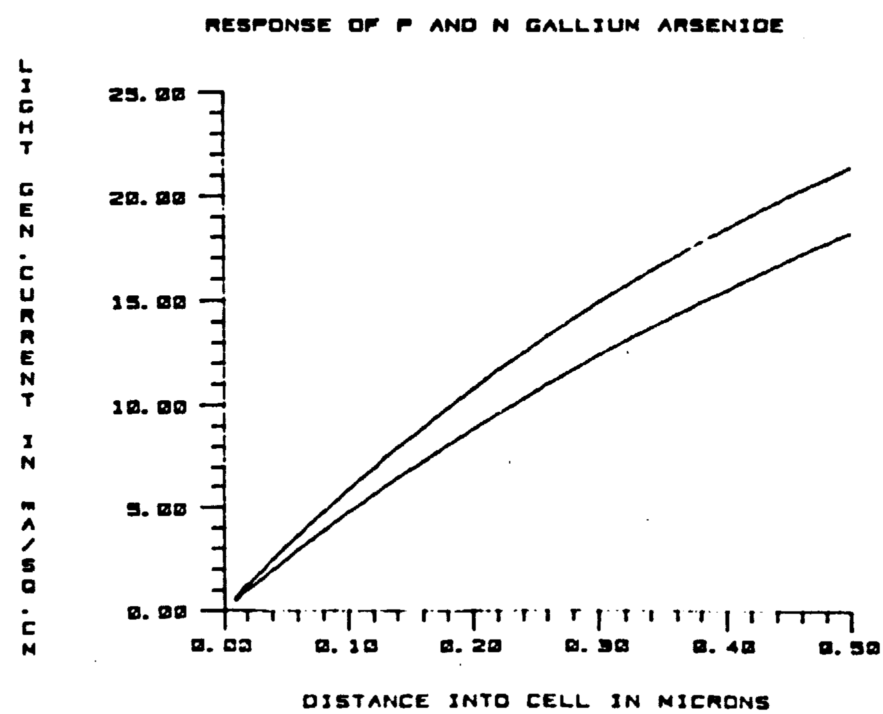


Figure 1. Maximum current from P and N GaAs as a function of thickness

Voltage Generation

The maximum voltage can be determined from the energy gap, the nature of the diode leakage current and the minority carrier diffusion length. An ideal diode is considered for this 100X solar cell.

Power Maximization

The primary power losses are due to top contact (grid) shading and series resistance losses. The resistance is primarily due to the top contact and the lateral currents in the top semiconductor layer. These optical and resistive losses can be held to 4 percent each based on a design to be discussed later.

Performance Comparison and Analysis

The optimized performance of the N on P and P on N structures is shown in Table 1.

TABLE 1

Geometrical and Electro-optical Properties of
Optimized N on P and P on N 100X GaAs
Concentrator Solar Cells
(4 millimeter diameter circle)

	N on P	P on N
Geometrical Properties		
Window Layer	GaP	GaP
Minority Carrier Collector		
Thickness	0.13μ	0.7μ
Doping	10^{19}	10^{19}
Photon Absorber and Buffer		
Doping	$10^{[illegible]}$	10^{17}
Thickness	10μ	10μ
Substrate Doping	5×10^{18}	5×10^{18}
Electrical Properties		
Voc	1.1 volts	1.07
Jsc	.427A	0.421A
FF	.852	.845
Grid Transparency	96%	96%
Resistive Power Loss	4%	4%
Maximum Efficiency	23.46%	22.36%
Unidentified Losses	5%	5%
Minimum Efficiency	22.29%	21.24%

Although the efficiencies of these two structures are similar, the role of the top semiconductor layer in the devices is vastly different. This top layer is normally transparent to most of the light and serves to collect minority carriers and convert them to majority carriers. In the N on P structure, .074 Amps or 15.2% of the total available current is generated in this top N layer. In contrast, for the P on N structure .33 Amps or 67.8% of the total available current is generated in this top layer.

If a primary degradation mechanism for space operation is the reduction of minority carrier diffusion length in the top layer due to particle bombardment, then the high amount of current generated in the top layer of the P on N structure is undesirable. Reducing the P layer thickness is undesirable because more carriers would be generated deep into the N material and subsequently not be collected.

Accordingly the N on P design is preferred.

2. <u>Transparent Contact (Grid)</u>

The standard transparent contact used for circular concentrator solar cells consists of concentric rings and spokes as shown in Figure 2 for a 1.24 cm diameter solar cell (designed by Varian Associates). This design assumes a 2 micron metal thickness and a 6 micron width.

3. Window Layer

As previously described, the (GaAℓ)As window layer served to reduce the surface recombination velocity of the top GaAs layers to minimize window absorption. This layer can have as much as a 9:1 Aℓ to Ga ratio. This large amount of Aℓ leads to difficulties in forming ohmic contacts to the window. Since AℓAs is hydroscopic, these contacts may deteriorate when exposed to air during module assembly and other ground-based operations. Additionally, deterioration of the window layer may lead to extraneous photon absorption which will reduce the light generated current.

These problems can be solved by using a GaP window layer. GaP has a band structure similar to AℓAs. It has a 4% lattice mis-match with GaAs, unlike the lattice matched AℓAs. This lattice mis-match will cause strain in the GaP, but since the GaP is electrically inactive, these strains should not reduce the efficiency. The lattice mis-match may also increase the GaAs recombination velocity, but since only 15.2% of the photons are absorbed in the thin N-layer, a two order of magnitude surface recombination velocity increase will have a minimal effect on the generated current.

FIGURE 2

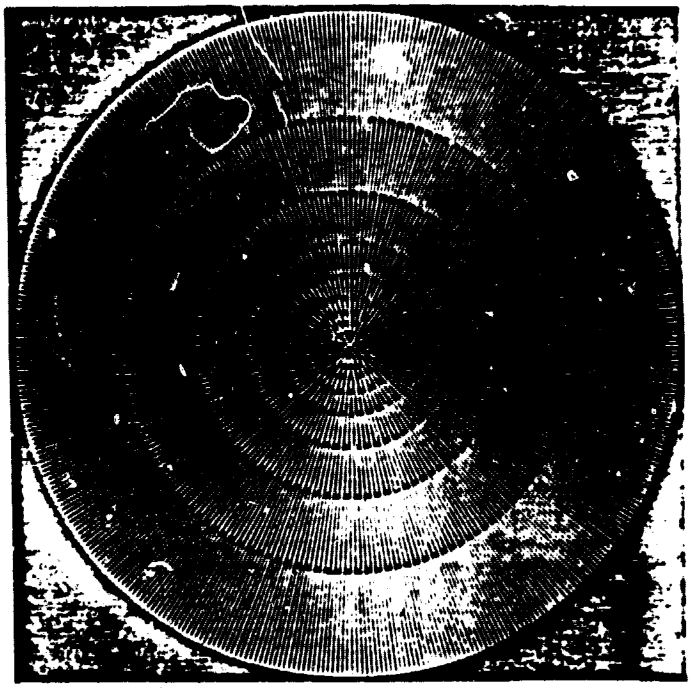


Fig. 2. Top-contact grid pattern of a Varian cell 0.49 in in diameter.

It has been shown on large area rectangular solar cells that a fine grid connected to the outside world with thicker bus bars maximizes the optical transparency while minimizing the series resistance. This bus bar and grid concept has been adapted to the cylindrical coordinate design of this 4mm diameter solar cell as shown in Figure 3. The grid lines are 2 microns wide and high and the bus bars are 10 microns wide and high.

FIGURE 3

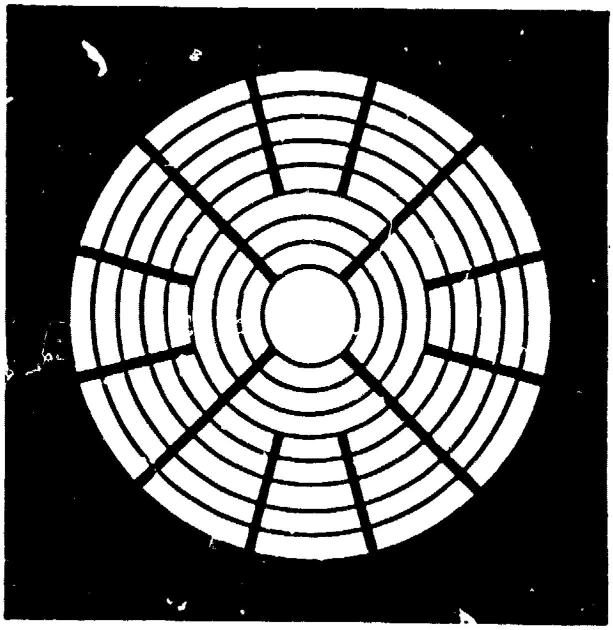


Figure 3. Grid and bus bar top contact design

CONCLUSIONS

A detailed accounting of all the photons can lead to a solar cell design which will achieve maximum efficiency. The GaAs maximum performance design will utilize (1) an N or P configuration, (2) a bus bar and a grid transparent contact design for minimum power losses, and (3) a GaP window layer for reduced optical degradation and contact degradation when exposed to air. This maximum efficiency solar cell can significantly improve the system efficiency and reduce the cost for solar arrays based on miniaturized Cassegrainian type optical concentrator elements.

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